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INFLUENCE OF HYDRIDE DISTRIBUTION ON FAILURE OF ZIRCALOY-4 SHEET

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Funded by the Fermi Consortium

NSRC, October 28-30, 2002

Industrial Context

- Nuclear Industry wants to **increase fuel burnups** (residence time in reactor):
  - Fuel savings; longer fuel cycles, => higher capacity factor
  - Reduction in waste volume (less fuel assemblies for same power produced)
- Increased burnup => increased radiation damage, but also increased oxidation and associated hydriding of cladding
- **Problem**: can highly hydrided Zircaloy-4 cladding withstand severe loading conditions associated with postulated licensing accidents? (i.e., is it safe to operate fuel at high burnup, what are the limits?)

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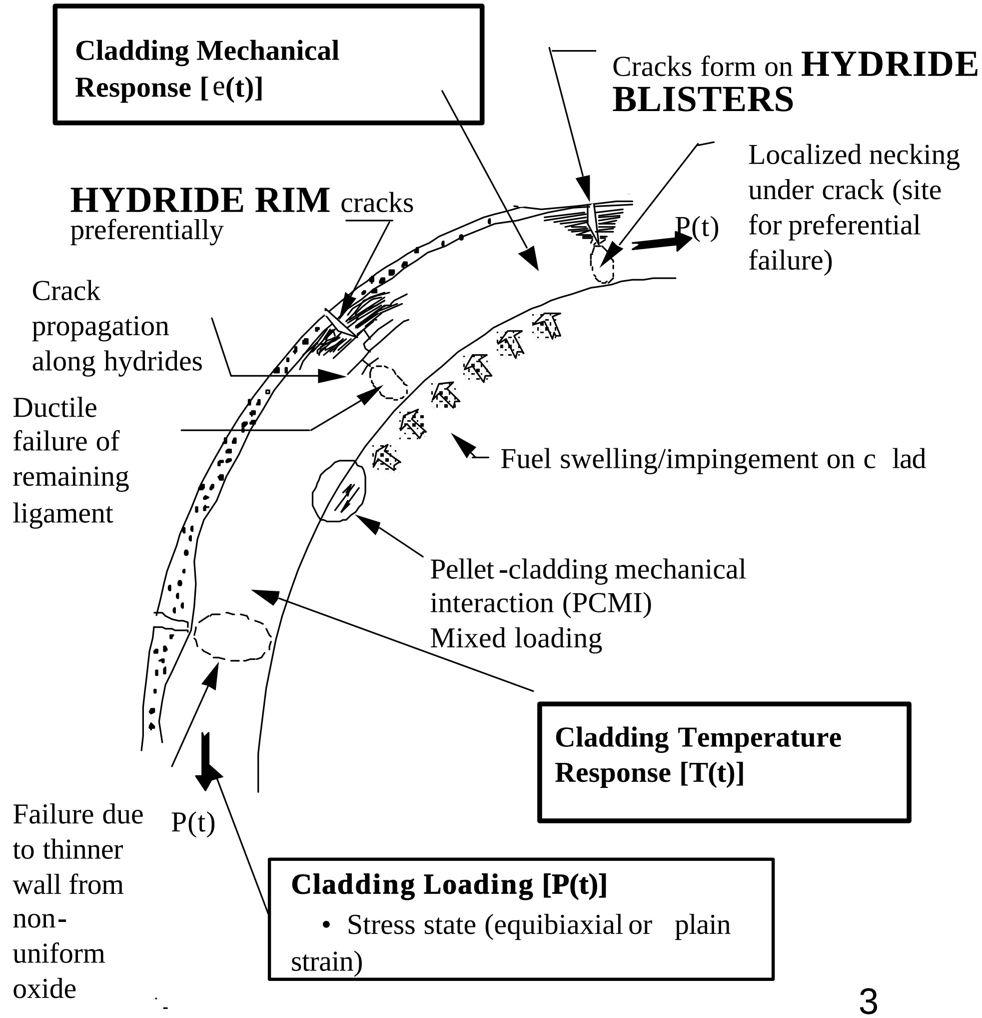
Effect of Hydrogen

- H affects cladding behavior.
- Two H distributions:
  - **Hydride "rim"**
    (temperature gradient from heat flux during operation)
    ⇒ Investigated (PSU)
  - **Hydride "blister"**
    (oxide spalling creates local "cold" spots where H aggregates)
    ⇒ This study

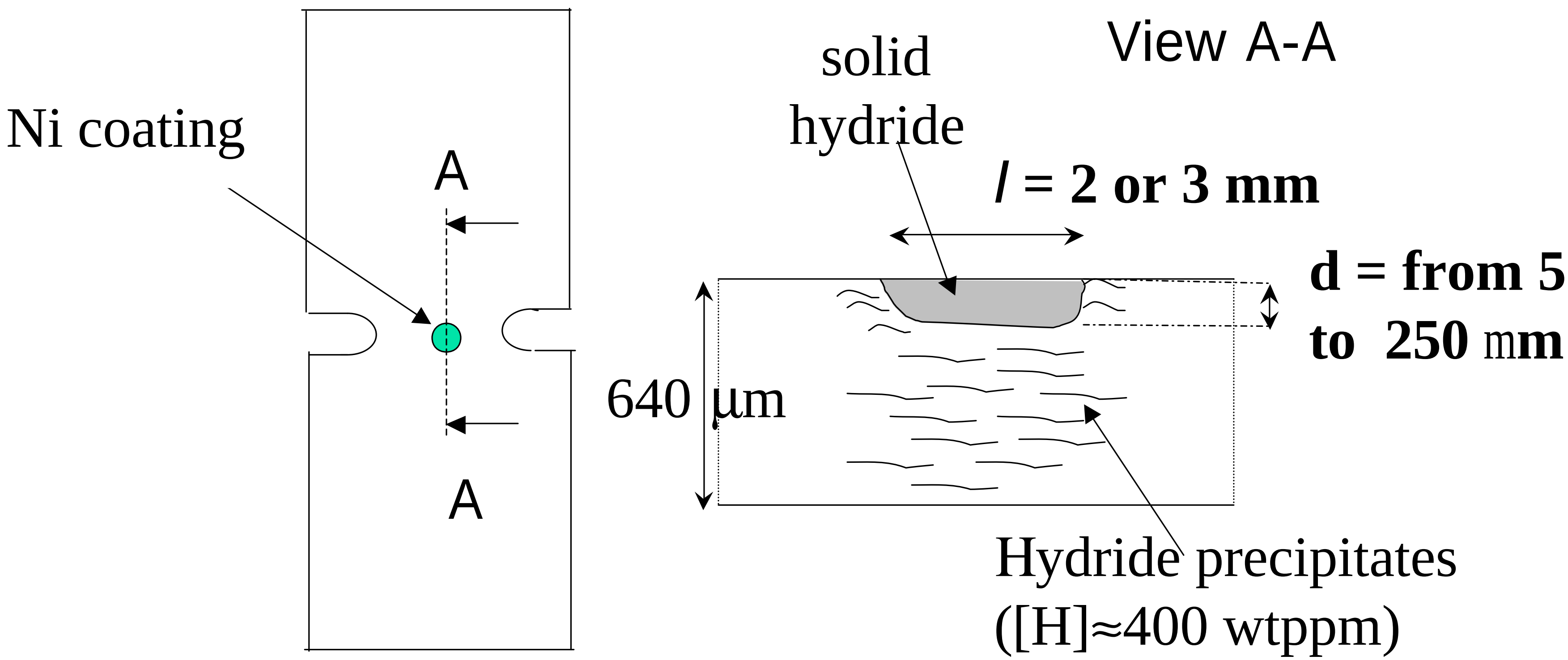


This Study: Hydride “Blisters”

- Experimental procedure:
  - Developed a new procedure that **simulates** the presence of hydride blisters on unirradiated Zircaloy-4 flat sheet with texture similar to tube.
  - **Plane-strain tension** (multi-axial stresses).
  - Two testing temperatures: **25°C**, **300°C**.
  - Two materials: **RX**, **CWSR**.

Hydride Blister Formation

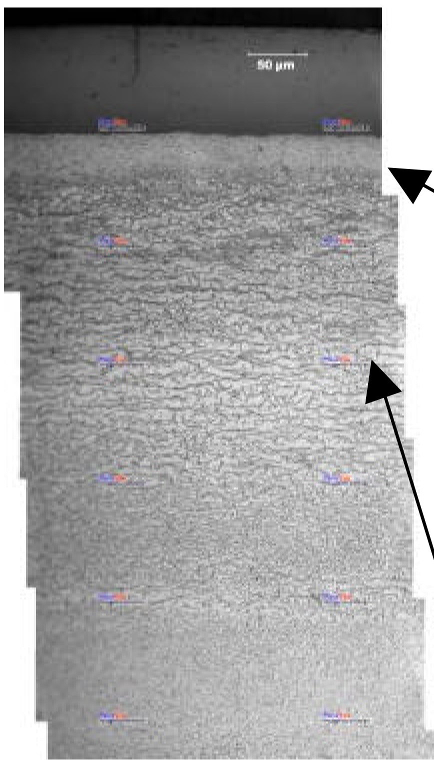
- Gas charging at 400°C



Comparison with Cladding

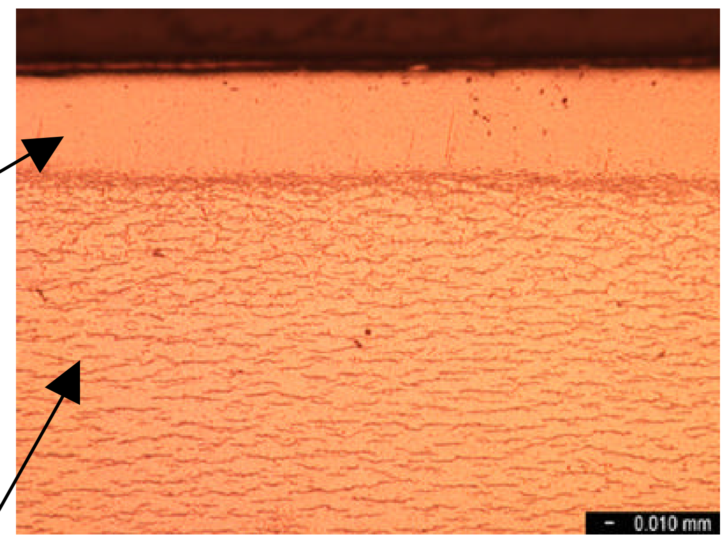
- **Irradiated cladding** (av. fuel burnup of 67 GWd/t and fast fluence of 1.3×10^{22} n/cm^2)

- **PSU Hydriding** (H_2 gas charging at 400°C)



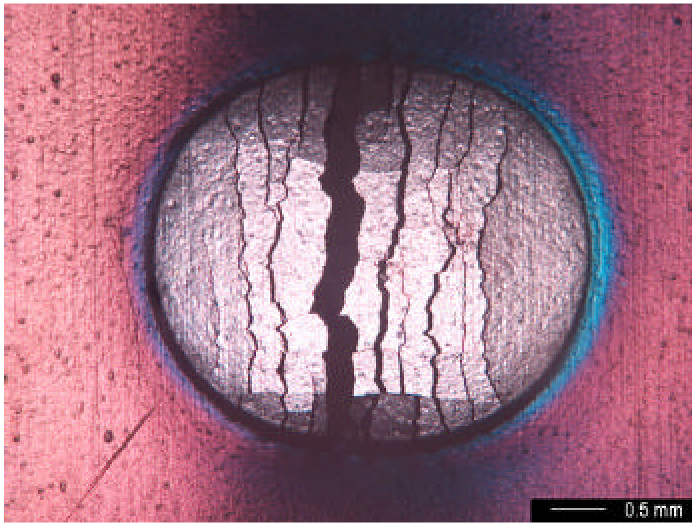
Solid hydride

Discrete hydrides

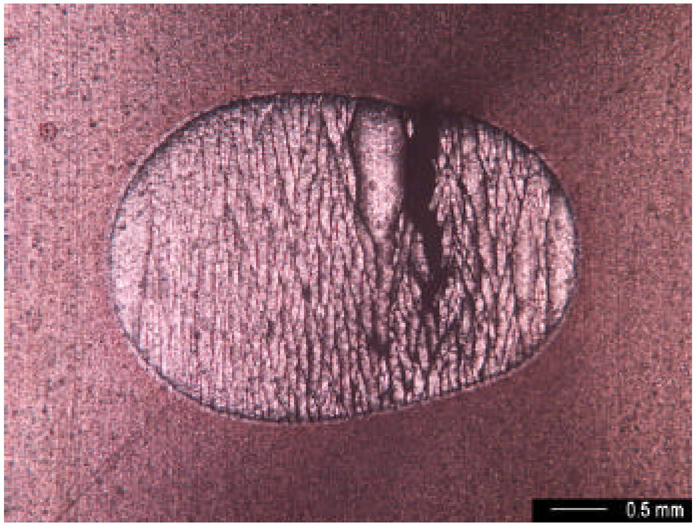


Fracture of "Blisters"

- Formation of **micro-cracks** upon yielding (detected by Acoustic Emission).



Blister Depth: 215 μm



Blister Depth: 40 μm

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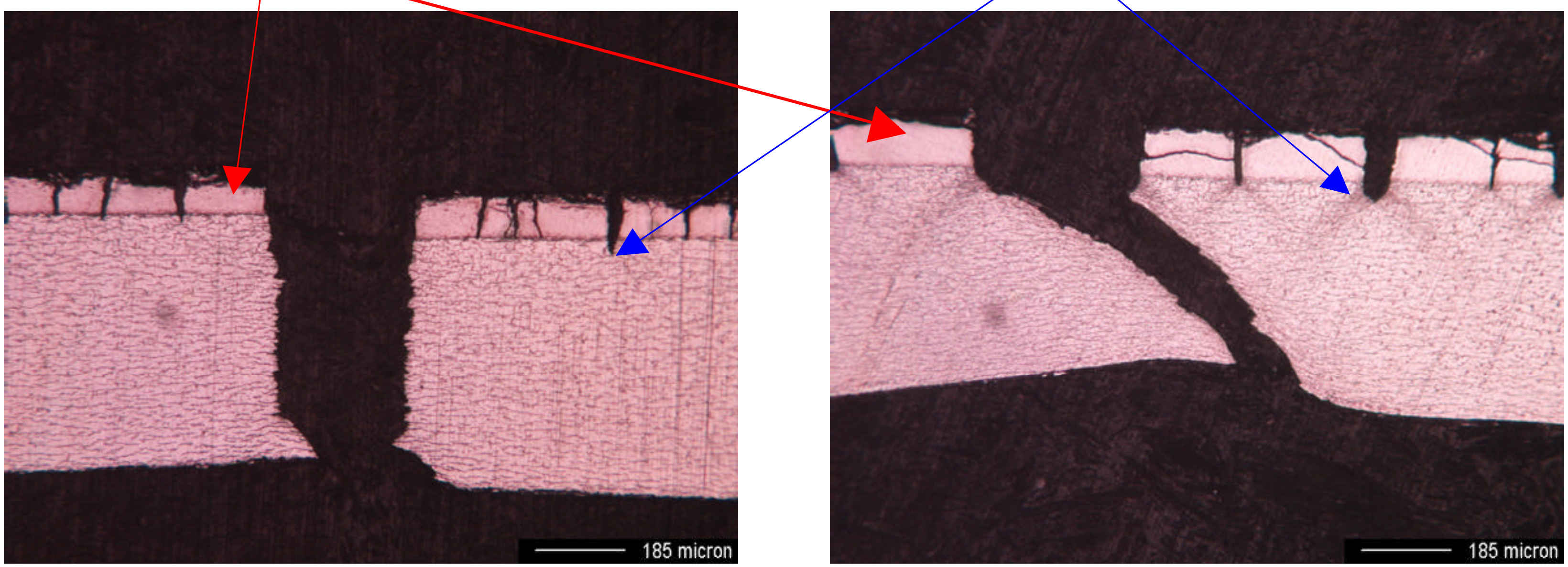
Fracture Profiles

- *Crack Growth vs. Shear Instablility*

Hydride Blister

Arrested micro-cracks



25°C 300°C

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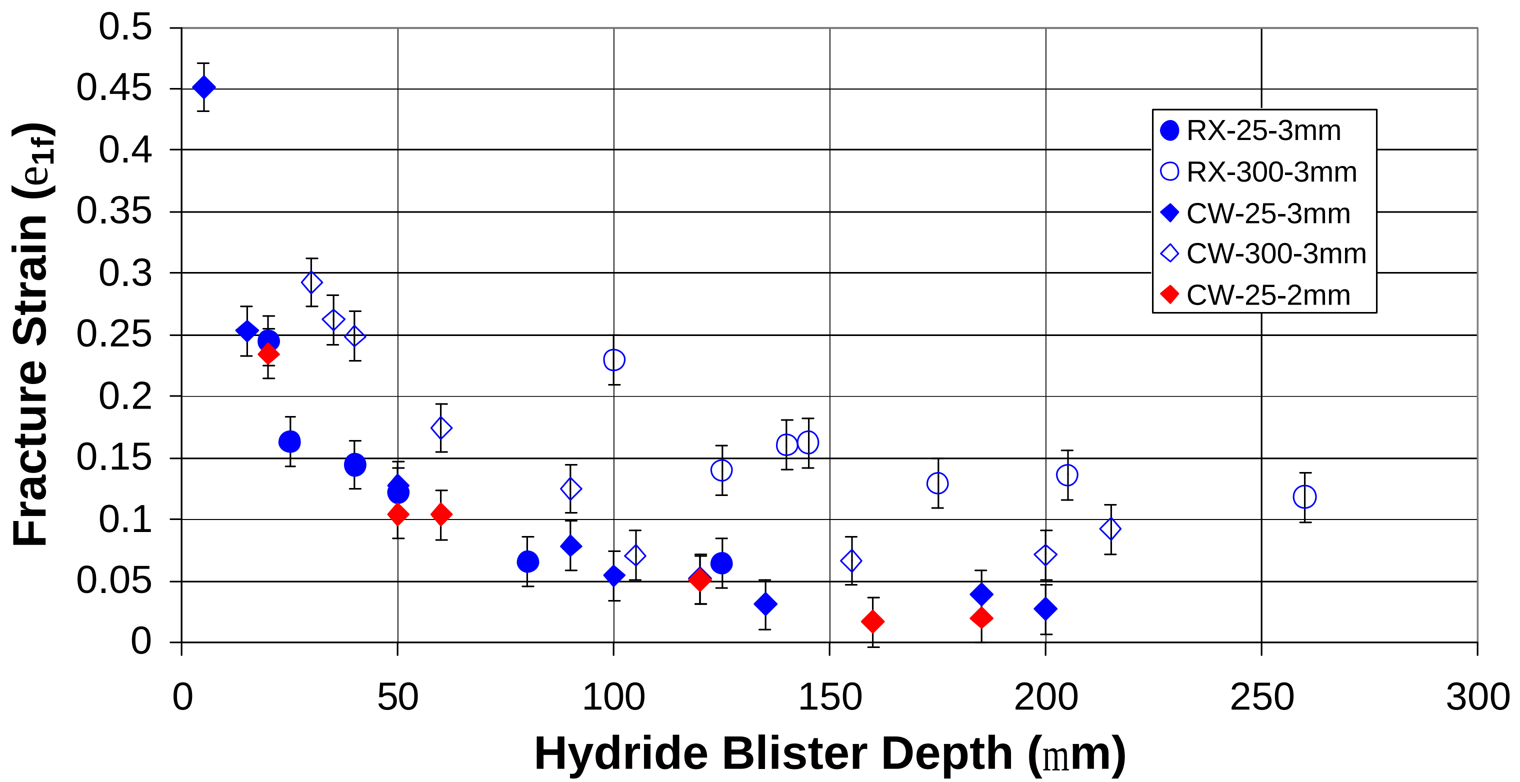
Specimen Ductility

- 2 & 3-mm diameter blisters



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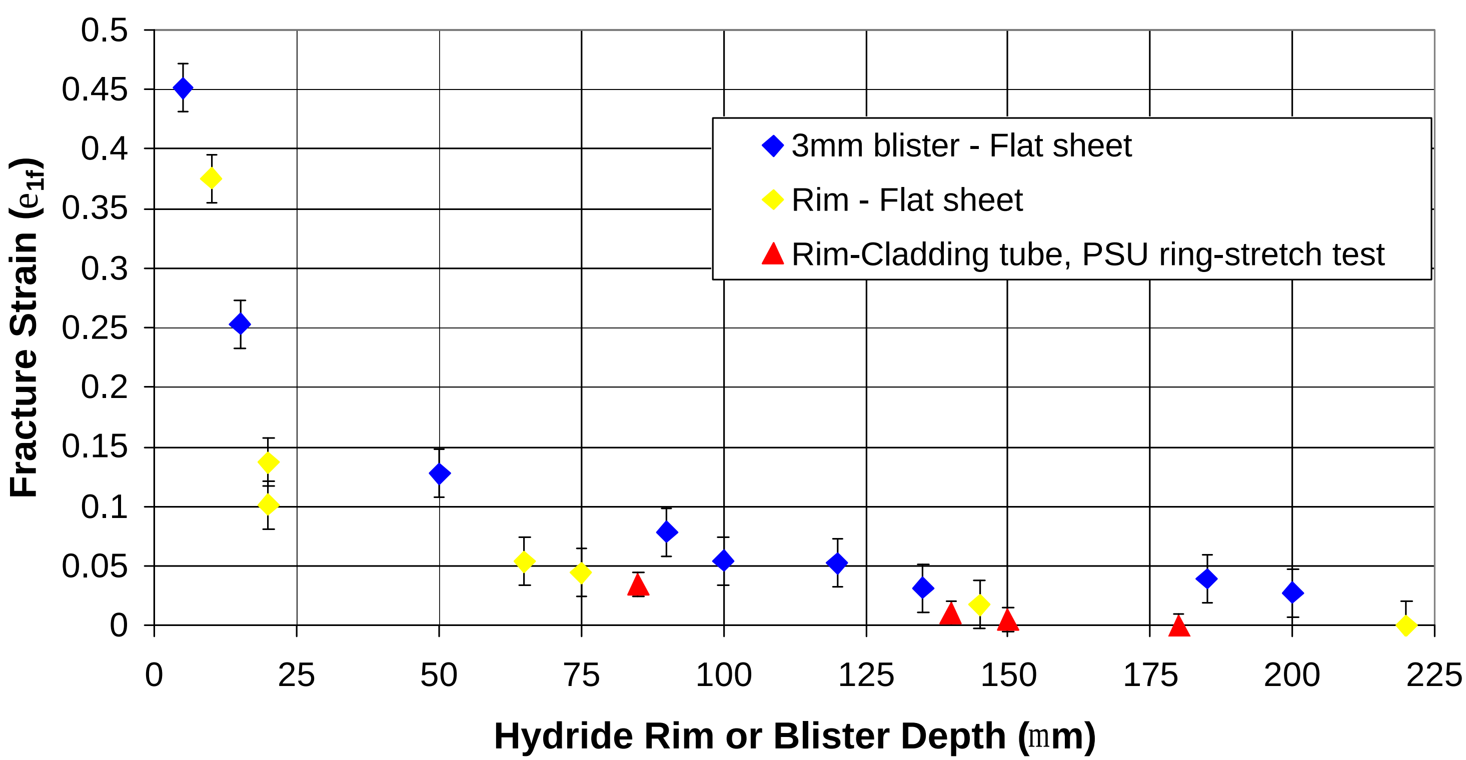
Specimen Ductility

- Significant decrease in ductility at 25°C w/ increasing blister depth > 25-50μm and plateau beyond ≈120μm.
- Similar ductility between 2-mm and 3-mm diameter blisters.
- Hydrogen embrittlement less severe at 300°C than at 25°C for given blister depth.

Specimen Ductility

- Blister vs Rim for CWSR at 25°C⇒ **Rim slightly more severe** (same at 300°C)



Summary of Results

Zircaloy w/ 2 or 3 mm-diameter blisters (5 to 250μm thick) + hydride precipitates in substrate

- Blisters crack upon yielding.
- As blister depth ↑ fracture strain ↓ (roughly independent of blister width)
- For given blister depth:

$$(\varepsilon_{frac})_{RX,25} \approx (\varepsilon_{frac})_{CW,25} < (\varepsilon_{frac})_{CW,300} < (\varepsilon_{frac})_{RX,300}$$

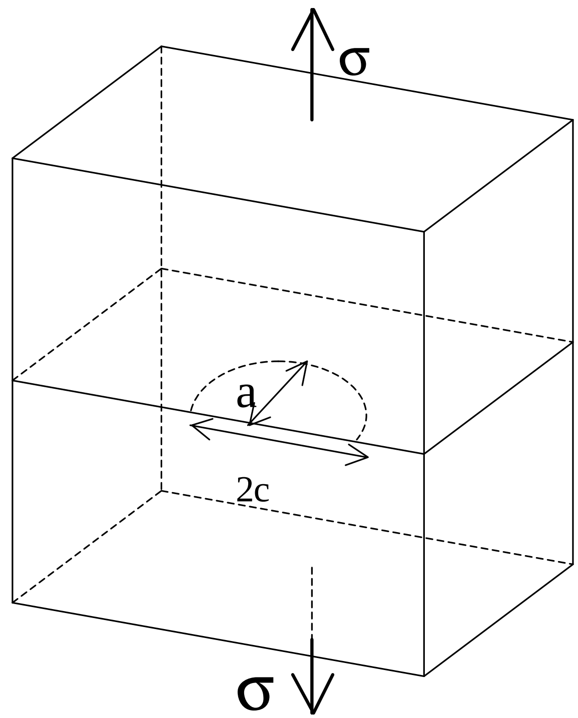
Summary of Results

- Fracture of sheet / cladding controlled by failure of substrate below blister:
  - At 25°C: crack growth on plane normal to σ_1.
  - At 300°C: shear instability on plane 45° to σ_1.
- Can we **predict** these results?
  - 25°C----fracture mechanics analysis
  - 300°C---analysis is still incomplete

Fracture Mechanics Analysis

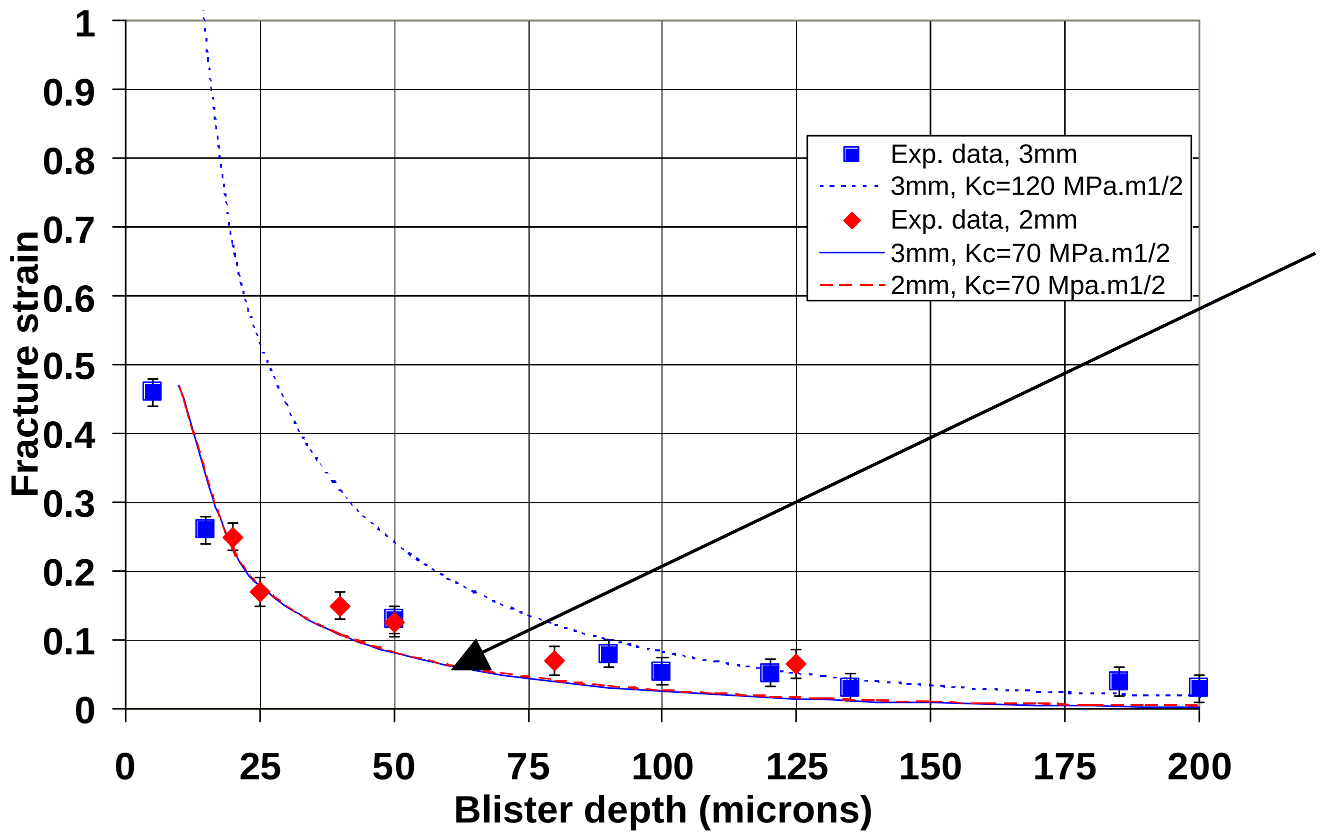
- Assumptions:
  - Single crack w/ depth = blister depth
  - Through-thickness plane stress conditions
  - J-integral procedure
  - Plastic zone correction
- Fracture occurs when:

$$\varepsilon_n^p = \alpha \frac{\sigma_0}{E} \left\{ \frac{1}{\alpha} \left(\frac{K_c^{\ 2}}{K_e^{\ 2}} - 1 \right) \right\}^{\frac{n}{n-1}}$$



Fracture Mechanics Analysis

- CWSR material at 25°C with two levels of fracture toughness:



Modeling **similar** for 2mm and 3mm wide cracks

Fracture Mechanics Analysis

- At 25°C, fracture mechanics predicts exp. results for a reasonable $K_c \approx 70$ MPa.m$^{1/2}$, in accordance with fracture profile (crack propagation).
- At 300°C, fracture toughness $\uparrow$ and failure occurs by **competing mechanism** $\Rightarrow$**shear instability** (fracture mechanics no longer applies)

Summary

Zircaloy w/ 2 or 3 mm-diameter blisters (5 to 250μm thick) + hydride precipitates in substrate

- Blisters crack upon yielding.
- As blister depth ↑ fracture strain ↓ (roughly independent of blister width, $(K_I)_{2mm} \approx (K_I)_{3mm}$)
- For given blister depth:

$$(\varepsilon_{frac})_{RX,25} \approx (\varepsilon_{frac})_{CW,25} < (\varepsilon_{frac})_{CW,300} < (\varepsilon_{frac})_{RX,300}$$

Summary

- Fracture of sheet / cladding controlled by failure of substrate below blister:
  - At 25°C: crack growth on plane normal to σ_1 (predicted for $K_c \approx 70$ MPa.m$^{1/2}$).
  - At 300°C: shear instability on plane 45° to σ_1.
- Fracture of substrate depends on ease of void nucleation at hydrides. At 25°C, hydrides crack / voids coalesce. Not so at 300°C where $(\varepsilon_N)_{300} > (\varepsilon_N)_{25}$ and shear instability develops.